Electronic Fingerprints For Machine Control and Production Machines

[0001] This application claims the benefit, for purposes of priority under 35 U.S.C. Sec. 119(e), of U.S. Provisional patent application no. 60/305,199, filed July 13, 2001, and for purposes of priority under 35 U.S.C. Sec. 120, the following U.S. patent applications, the contents of which are hereby incorporated by reference herein in their entirety: U.S. patent applications 09/950,848, 09/950,726, 09/950,723, and 09/950,731, all filed on September 12, 2001, and 10/052,293 filed January 18, 2002. This application is a continuation of U.S. patent application Serial No. 10/226,979, filed on August 23, 2002.

Field of the Invention

[0002] The present invention relates in general to machine control and production machines and, in particular, to monitoring, measurement and maintenance in connection therewith.

Background

[0003] Trace functionality is available in automation systems and drives, as are trace-selectable feedback or fixed parameters or process values. All parameters of a controlled process may be traceable when such functionality is available. For example, it is normal practice today to employ trace functionality to control currents or motor currents. Trace functionality is used to set up the controls associated with a production machine. Trace functionality, however, is not believed to have been used to develop or bring about new features in drive control, motion control or numeric control, nor is it

believed to be used to describe the characteristics of a production machine or to generate such characteristics for use in the improvement of the quality of controlled processes or the products they generate.

Summary of the Invention

[0004] The present invention overcomes at least some of the deficiencies of the art described above, and many others by providing machine fingerprints and systems for the generation and use.

[0005] One aspect the present invention is directed to an electronic fingerprint apparatus for a machine. The apparatus comprises an automation component having a controller for controlling movements of at least one component of the machine, the automation component adapted for capturing electronic fingerprints representative of a state of the machine. The apparatus further comprises a fingerprint device for selecting for measurement a plurality of movements of the machine to generate an electronic fingerprint that is representative of a condition of the machine.

[0006] Another aspect of the present invention provides a method for generating electronic fingerprints of a machine. The method comprises the steps of selecting for measurement parameters associated with at least one component of the machine that are representative of a condition of the machine, reading the parameters and storing the read parameters, thereby creating an electronic fingerprint representative of a condition of the machine.

Brief Description of the Figures

[0007] Figure 1 shows in schematic form, along with associated control-related equipment, an automation component for determining electronic fingerprints of a machine tool or production machine, in an embodiment of an aspect of the present invention.

[0008] Figure 2a shows an embodiment of an electronic fingerprint according to an aspect of the present invention, showing a normal condition of a machine.

[0009] Figure 2b shows an embodiment of an electronic fingerprint according to an aspect of the present invention, showing an abnormal condition of the machine for which the normal fingerprint was depicted in Figure 2a.

[0010] Figure 3 shows a graph of measurements obtained from an operation for changing a periodic error in the pitch of a ball screw, illustrating an embodiment of an aspect of the present invention.

[0011] Figure 4 shows, schematically, states associated with a deterioration of the ball screw of Figures 2a, 2b and 3.

[0012] Figure 5 shows a graph depicting the behavior of the worn ball screw represented in Figure 3.

[0013] Figure 6 shows cyclic deviations in a signal representing a direct measurement of cyclic pitch errors associated with the ball screw, in an embodiment of an aspect of the present invention.

[0014] Figure 7 shows another embodiment of an aspect of the present invention in the context of a measurement of backlash in a gear box.

[0015] Figure 8 shows the influence of backlash on a measured signal associated with the gear box, measurements of which were shown in Figure 7, the influence being due to mechanical wear in the gearbox.

Detailed Description

[0016] As used in describing the various aspects of the present invention, "electronic fingerprints" of a machine tool or a production machine include a set of measurements that are characteristic, and document the behavior, of the machine. Machine control and production machines have variations in their behavior that make each machine unique. These unique behavioral traits may be truly machine-specific, differing even as between machines of the same type and character, or of the same model and that are otherwise seemingly identical. No matter how similar two machines may appear, an aspect of the present invention recognizes that they will always have some unique behavior that can be isolated and documented to identify a condition of the particular machine. The differences between machines generally grows more pronounced over time. The operation of the machine may, and indeed often does, alter its working components or their alignment or position, thereby changing the behavioral characteristics of the machine. The set of behavioral characteristics that uniquely identify a particular machine are within the definition of the term "electronic fingerprints," as used here.

[0017] A method according to one aspect of the present invention determines, for any particular machine, the set of characteristics that uniquely identify the condition or state of that machine. Another aspect of the present invention involves identifying which measurements will capture unique characteristics of a production machine. That is, the identified measurements characterize the individual characteristic of the machine. Also according to an aspect of the present invention, it is optimum to identify a minimal set of behavioral characteristics that identifies the particular machine. In addition, the electronic fingerprints according to the present invention are derived such that, no matter how the fingerprint evolves over time, a fixed fingerprint system is developed so that the machine condition can be identified over time.

[0018] Use of electronic fingerprints according to the present invention confers many advantages. For one thing, their use allows the operator to check the instantaneous condition of the machine. Further, changes in the behavior of a machine can be determined by comparison of certain measurements representing an initial state to those representing a later state of the machine. The resultant deviation can yield evidence as to the machine's condition and its present and future performance. The measurements may be repeated periodically to further analyze machine behavior. Electronic fingerprints can thus be used according to another aspect of the present invention for predictive maintenance by using the fingerprint to indicate an existent or eventual condition of the machine, before the condition is otherwise detectable.

[0019] Figure 1 shows an automation component 10 that makes mechanisms available

for determining electronic fingerprints according to an aspect of the present invention. The automation component 10 may, for example, be part of a machine tool or other production machine. A controller 12a (e.g., a PLC) provides for logic control, and the mechanical component that is driven by the controller (e.g., motion control or numeric control) 12b provides for the control of the motion of mechanical parts of the production machine and associated workpieces. As an alternative, one controller could perform both the logic and motion control tasks. A user interface 16a provides the user with a screen or other interface for the monitoring and control of the automation component 10.

[0020] A separate user interface 16b provides a user interface having an engineering system and provides for the setup, configuration, and programming of the automation component. The user interfaces 16a and 16b, in one embodiment, might run on one hardware platform. In addition, remote access to a remote PC 18, for example, through a communication channel 20, such as the Internet or Intranet, may be provided by an appropriate interface and TCP/IP, Ethernet, or other network. An analysis 22 of the machine can be derived and displayed at the remote PC, for example. A machine data server 14 is linked to the automation component. The present invention specifically provides means for identifying the state of the machine and/or product, and an associated condition, by means of a fingerprint of the machine at a given time. The automation components provide means for capturing fingerprints of the machine.

[0021] Additional input/output signals are provided, depending on the type of machine

being controlled. Here, for example, an input/output rack is provided for inputting and outputting signals 24, such as those associated with a programmable logical controller (PLC). Also provided is an axis mechanism 26, which controls an axis of a movable piece of the machinery, such as robotic arm, drill press, etc. The machine may also be coupled to other processors, such as via a communication network 28.

[0022] In order to obtain and analyze the fingerprints, the present invention provides a graphical user interface (GUI) 18. This may, for example, be a human machine interface (HMI) that is modified, according to the present invention, to "lift," store and examine the fingerprints. The interface could be provided, for example, on a host PC and connected to the automation component by a communication interface, such as the Ethernet or Internet. With the interface provided, the fingerprints can be evaluated manually or automatically according to a particular description as set forth below.

[0023] As already indicated, an aspect of the present invention involves knowing which measurements to make in order to reveal the electronic fingerprint. The technique may vary according to the type of machine involved. For example, machine tools having a cutting function can be caused to undergo a test trace function. However, other machines, such as a pump, may have no trace capability. The present invention includes various techniques, dependent on the type of machine, to develop, or "lift", the electronic fingerprint. The recognition of the fingerprints is realizable using various techniques.

[0024] Fingerprint functionality according to the present invention can be implemented in the system software of the automation component 10. As already mentioned, electronic fingerprints can be realized concretely using, for example, an application of a trace test for machine tools having a trace functionality with a numerical control. In another aspect of the present invention, the automation component includes an easily programmable expiration operational sequence. Using such application programs, the fingerprints can be developed or "lifted." The automation component makes suitable Application Program Interfaces (API) accessible to an application program for taking up of fingerprints.

[0025] If the condition or state of the machine is regarded is its fingerprint, lifted using programming applications, for example, the programming signals might be thought of as the "dust" with which the fingerprints are formed. These signals may, for example, be internally accessible signals that are suitable for documenting the quality of an expiration or a process. The process-specific parameters are defined accordingly. Also, any of the measured values of drives, parameters from motion controllers, production machines or format data from the application program may be utilized.

[0026] In one example, the signal may be measured from distinct, event-controlled signals that are generated cyclically or during a certain period. For another, the measured signals are derived from the control and/or by control/application via auxiliary sensor technology. If necessary, the auxiliary sensor technology could include, for example, accelerometers.

[0027] As shown in Figure 2a, the electronic fingerprint 30 of the present invention can be visualized as a two-dimensional graph. As shown, the parameter points 32, whose values are indicated by the position in the matrix 34, are connected by the dashed lines 36. In this manner, it can be readily seen that the electronic fingerprint of the present invention is similar to an actual fingerprint in the sense that it maps out an imprint that is characteristic of the machine from which the electronic fingerprint is lifted. The fingerprint shown in Figure 2a is a simplified representation of what could otherwise be expressed as a complex array of parameter points and that can also be represented as an n-dimensional fingerprint displayed as a computer graphic.

[0028] As will be appreciated from Figure 2, the condition of the machine can be determined from the fingerprint. Figure 2b, for example, shows a fingerprint that reveals an abnormal condition. Illustrated by the deviation 38 (indicated by the arrow), the condition represents a departure or variance from the abnormal fingerprint of Figure 2a. The variance 40 can be thought of as an area underneath the portion of the fingerprint lying outside the healthy fingerprint. Fingerprints can be stored in advance in a database and later compared. Also, abnormal fingerprints can be collected over time to form a database for future reference in other applications. The electronic fingerprints according to the present invention are clearly advantageous for analyzing machines in this manner because of the ease with which they identify any deviations. Particularly useful is their ability to permit visual inspection of the fingerprints by a user. At a glance, they can reveal whether the machine is in an error condition or not.

[0029] The fingerprint may be representative of a plurality of machine-related states, including, for example, a machine behavior. The fingerprint may also be representative of product quality, which may depend on both the machine and the material. In the example of Figures 2a and 2b, the fingerprint may indicate, in a laser cutting machine, a special relationship between the speed of movement of the laser and its power. If, for example, the relationship is not maintained in the correct fingerprint (Figure 2b) the laser will move too slowly and burn holes in the work piece. On the other hand, the laser may move too quickly and fail to cut the material. When the process is stable, as in Figure 2a, then the product quality can be assured, i.e., that the work piece is properly cut by the laser in this example.

[0030] As with any fingerprint, the electronic fingerprint is developed for analysis, a sort of electronic sleuthing. The evaluation (e.g., PC) software, as described above, runs an automated comparison/evaluation of the fingerprints. The results of the comparison/evaluation have wide application, including, without limitation, preventing recognition of machine wear, quality assurance, maintenance, production data collection, error evaluation, documentation of the error, identifying delivery status or condition after software boot up and automatically correcting errors. In error evaluation for diagnostics, in particular, the fingerprints can be derived when the machine is running improperly. This is preferably achieved when the machine is running certain critical procedures, from which conclusions may be drawn as to possible errors.

[0031] The generation of the fingerprints can be achieved using the following applications, for example. Parameters for the fingerprint may be obtained from the engineering system, or other suitable source. Control parameters may be sensed in the course of configuring monitoring points, for example, and which axis is to be controlled. Otherwise, the parameters may be obtained upon configuration of the observation parameters (e.g., situation layer, moment actual values, observer values, application variables, etc.). The fingerprint parameters may also be developed from the parameters resulting from a start and stop event for recording projections or over application program control.

[0032] In another manner according to the present invention, the fingerprints can be produced at the software vendor end. This can be achieved by marking appropriate attributes of the relevant data/variables during programming of the software. This is supported by the Engineering System (Figure 1, 16b) of the automation component. The measurements may be taken, for example, from the trace information. In addition, the vendor can provide for the measurements along with the evaluation software for evaluation using the evaluation PC. Evaluation software for comparison of the fingerprints may be provided, for example, according to an aspect of the present invention. The application software, software for fingerprint production (running in the automation component) and evaluation software (running in the evaluation PC) can be provided in any of the known, or equivalent, programming languages, including Java, for one example.

[0033] The fingerprint application can be applied according to various methods of the present invention. In one method, the fingerprint application is downloaded through the PC communication connection to the machine, i.e., automation component. Further, the application can be applied by deliberate machine service personnel, via an external service branch. The fingerprint application could be started automatically by the application program itself, during certain maintenance or time intervals, during reequipping procedures, or at other suitable times. Additionally, the fingerprint program may be implemented by remote operation, for example, over the Internet. Also, the fingerprint measurement application can be optionally supported by a deposited workflow. In accordance with another aspect of the present invention, the user manually performs measurement of the fingerprints of the selected machine and causes the PC to note target/actual conditions, such as occur cyclically over a certain length of time, for example.

[0034] Like all fingerprints, the electronic fingerprints may be profiled. The first step in profiling of the fingerprints is achieved by storing them in a suitable memory. In the machine/automation component, for example, the fingerprint can be stored on a hard disk, memory card or the like. Alternatively, the fingerprint can be stored on the data server of the machine (Figure 1 at 14), or on the evaluation PC, by remote file. The fingerprints may even be stored in additional machine information storage, such as production data or format information data.

[0035] Once fingerprints are stored, their profiling continues by conducting an

evaluation process. This process may take place in the evaluation PC and may be accomplished either manually or automatically. From the results of the analysis, adjustments to the machine may be derived. Composites of "healthy" fingerprints may be stored in advance in the evaluation software. These may, for example, be in the form of tolerances of the various machine components. A capability for such analysis permits the fingerprints to be evaluated or developed over time.

[0036] The structure of various aspects of the present invention has been described. Below are examples of actual applications employing the invention. The following examples illustrate operation of aspects of the present invention in regard to two types of machines, namely the production machine and the machine tool. In the former, the overall fingerprinting is concerned with the determination of product quality, or machine quality, or with both aspects. In contrast, the machine tool focuses on the determination of the machine quality, i.e., machine condition. As with many measuring procedures the quality of the processing material and the machine quality produce overlapping effects, and these examples are no exception. In any event, the following examples are described.

[0037] The first example concerns a packaging machine. It is desired, for example, to perform a pressure mark correction procedure, which corrects the pressure mark of the packaging machine. In this instance, measurements of the process are collated into an actual value profile. The same measurements can be derived from a fast pressure mark correction, when a fast correction is made. The actual value profile changes can

be compared over time. With such a comparison, the end product can be influenced directly.

[0038] In the same packaging machine, a real time view of the motion of the machine may also be viewed. Critical ranges in the total course of motion with a trace, for example, can be obtained. This could be performed, for example, with seam welding, such as in foil welding. Relevant parameters may be measured for a view of the process, and measured parameters may be the target values from the control and/or the drive. The measured values may also be actual values of sensor technology or process variables from the application.

[0039] Also provided is a kind of test operation, applying a test drive procedure for testing the machine. In the test operation, a cyclic machine clock of a packaging machine with a defined production speed cycles through critical sections of the course of motion. During this time the relevant actual values that occur are recorded according to an aspect of the present invention.

[0040] The above example is directed primarily to the operation of the machine. In an injection molding machine example, greater emphasis may be placed on the quality of the product. Here, the injecting process for a certain tool is examined. As with any given tool, prescription data may normally be provided, such as the profile, temperature attitude, etc. The prescription data is taken as the base fingerprint that is compared to actual data received over certain periods. The data is obtained from the injecting

process based, for example, the manner in which the pressure or strength of the injection is applied. The values may be compared, for example, in one embodiment, using an integral-based averaging algorithm, which is applied to values collected over a predetermined period of time. From the measured variables, load differences and aging influences of the tool, for example, can be derived. With this data, an improved influence over the quality of the end product may be obtained.

[0041] According to the foregoing description, a fingerprint for a machine tool or production machine may be derived to determine a condition of a machine or to monitor the quality of the production machine. With the foregoing fingerprint parameters it is also possible to troubleshoot existing problems. The following presents two simple examples in which such machine problems can be pinpointed by fingerprint measurements. The main technique applied measures the fingerprints periodically and compares the deviations of the results with the initial measurements.

[0042] Figure 3 illustrates a graph of measurements obtained from an operation for changing a periodic error in the pitch of a ball screw. It is assumed, according to the example, that the ball screw drives an axis, X. In addition to a motor measuring system, an additional linear scale is also provided along the axis X. The motor measurement system is used for closed loop control, while the linear scale is used as a measurement device during the present measurement. If the axis is moved with a constant speed along a certain travel area, X_0, the ideal behavior is shown in Figure 3.

[0043] The movement X(t) of the axis is ideal to demonstrate the value of the invention, as inaccuracies during the production process of the mechanical components of the machine are experienced in the actual world. For instance, it is very often the case that a real ball screw exhibits a cyclic error in the pitch in comparison to its ideal behavior. Due to mechanical forces, this error is magnified over a certain time period.

[0044] Figure 4 shows, from left to right, a deterioration of the ball screw over time and, in particular, over consecutively numbered discrete states. This situation is further illustrated in Figure 5, on a graph of the form shown in Figure 3. In Figure 5, in which the behavior of the worn ball screw is represented, the cyclic errors in the pitch are shown enlarged and in schematic form. It may be, for example, that the error of the ball screw is enlarged after a certain time of machining due to mechanical forces.

[0045] Now, if the error exceeds a certain period of time, the ball screw should be changed in order to avoid inaccuracies during machining. These errors can be measured in the following way according to the present invention. In the first instance, the axis is moved with a constant speed and only the motor measurement system is used for closed loop control. In this case, the motor moves with a constant rotation speed. The constant speed yields a constant rotation of the ball screw. The pitch error is translated to the linear scale, showing a periodic deviation from the ideal behavior, as is apparent from the figures.

[0046] In Figure 6, cyclic deviations of the signal of the direct measurement system in

case of cyclic pitch errors are shown, where the motor measurement system is used for closed loop control. In this case, the more the errors in the pitch are enlarged, the more there are likely to be deviations within the signal of the linear scale. At this time, if the axis is measured periodically in this way, it is possible to discern critical errors before work pieces are damaged. In other words, it is possible to change the ball screw at a point in time before the critical state is reached, rather than after a fixed period of time, or to change the compensation values for the screw pitch error automatically.

[0047] As shown in Figure 7, in another example, backlash detection is demonstrated. By means of the same method of the invention, it is also possible to detect, for example, a backlash in a gear box. Backlash may occur as a result of a build up of mechanical stresses. For this measurement, we move the axis forward and backward at a constant speed. Again, only the motor measurement system is used for closed loop control and the linear scale is used only for measurement purposes.

[0048] Ideally, the X(t) behavior would be as it is shown in Figure 7. As shown, X(t) of the direct measurement system includes no backlash as the axis is moved forward and backward at a constant speed. The influence of backlash on the measured signal, due to mechanical wear, for example, can be seen in Figure 8. As will be seen, due to the backlash in the system, the axis does not follow immediately. This is particularly apparent when the motor changes its rotation direction. At first, the axis stays at its current position and then moves back with a constant shift.

[0049] From the derived fingerprint, it is apparent that the errors can be determined earlier than when the critical state is reached and maintenance can be applied before breakdown of the system. It is possible, for example, to predict problems arising due to backlash by periodically repeating the measurement and checking whether a pattern of critical deviation occurs in comparison to the initial state of the machine has been reached. In addition, it will be appreciated that the degree of maintenance can be varied according to the fingerprint of the present invention. That is, there are degrees of abnormality of a fingerprint and, depending on the degree, it may be determined that maintenance is not yet needed. On the other hand, the fingerprint may be employed to determine minimum maintenance, deciding to allow the machine to continue to operate under less than optimum conditions, thereby better managing the maintenance of a machine.